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Laser Scanning System for Pressure and Temperature Paints

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CHAPTER 1 : INTRODUCTION

Acquiring pressure maps of aerodynamic surfaces is very important for improving and validating the performance of aerospace vehicles. Traditional pressure measurements are taken with pressure taps embedded in the model surface that are connected to transducers. While pressure taps allow highly accurate measurements to be acquired, they do have several drawbacks. Pressure taps do not give good spatial resolution due to the need for individual pressure tubes, compounded by limited space available inside models. Also, building a model proves very costly if taps are needed because of the large amount of labor necessary to drill, connect and test each one. The typical cost to install one tap is about \$200.

Recently, a new method for measuring pressure on aerodynamic surfaces has been developed utilizing a technology known as pressure sensitive paints (PSP).¹ Using PSP, pressure distributions can be acquired *optically* with high spatial resolution and simple model preparation. Flow structures can be easily visualized using PSP, but are missed using low spatial resolution arrays of pressure taps. PSP even allows pressure distributions to be found on rotating machinery where previously this has been extremely difficult or even impossible. The goal of this research is to develop a laser scanning system for use with pressure sensitive paints that allows accurate pressure measurements to be obtained on various aerodynamic surfaces ranging from wind tunnel models to high speed jet engine compressor blades.

PREVIOUS WORK

Only a short review of the literature will be given in this thesis, since a detailed review, including 104 references, was recently published by Liu, et al.¹ The pressure sensitive paint technique was first developed in the early 1990's by groups at the University of Washington and the Central Aero-Hydrodynamic Institute (TsAGI) in Russia. Since then, many other Universities and companies have been developing their own PSP methods. As such, there have been many experiments conducted using PSP. The majority of these tests have occurred in high speed flows where the pressure changes, and hence fluorescence intensity changes, are large enough to be easily detected with simple CCD cameras. Recently, more work has been concentrated on the use of PSP in low speed flows. In this flow regime, many difficult problems are being encountered as the limits of pressure sensitivity and data acquisition accuracy are neared.

WIND TUNNEL EXPERIMENTS

Wind tunnel experiments can be broken down into two basic categories: high speed and low speed experiments. The high speed experiments are fundamentally easier due to the larger intensity changes which are easier to detect. Initially, simple two-dimensional airfoils were tested in mid to high subsonic speed ranges. Kavandi et al tested a two dimensional NACA 0012 airfoil over a Mach number range of 0.3 to 0.66 in 1990². The PSP-derived pressures compared well to surface taps. Upper surface shock waves were identified at the high speed cases. McDonnell Douglas tested a generic wing/body model at Mach 2, a high performance fighter model at Mach 1.2 and a two-dimensional converging-diverging nozzle with good results in 1993³. In all of these tests, in-situ calibrations were used to get the pressure from the PSP intensity. This removes temperature effects and the complexity associated with its correction if the paint layer is isothermal.

The use of PSP in low speed flows is somewhat limited at the present time due to the relative insensitivity of PSP to small pressure changes. Recently, low speed

experiments using PSP have been conducted by Morris at McDonnell Douglas.⁴ These experiments were carried out at Mach numbers from 0.05 to 0.2 on a delta wing model. Good agreement between PSP and pressure taps is indicated.

ROTATING MACHINERY EXPERIMENTS

Pressure measurement in rotating machinery using traditional techniques is complex due to the difficulty in instrumentation. Pressure sensitive paints allow measurements to be taken much easier with higher spatial resolution. Pressure and temperature measurements on rotating machinery were acquired by Burns and Sullivan in 1995 using PSP and TSP.^{5,6} Tests were conducted on a small propeller (37 cm), a Hartzell aircraft propeller (92 cm) and an Allied Signal F109 turbofan engine. Results for the propellers indicated the correct trends, while pressure measurements were not completed in the F109 engine test. Significant problems were encountered due to the large temperature increases at high speeds, effectively quenching the pressure sensitive paint's fluorescence and significantly decreasing the signal-to-noise ratios. Keeping the paint on the compressor blades at high rotational speeds also proved to be difficult.

PSP THEORY

Pressure sensitive paint (PSP) is the general term describing a coating applied to an aerodynamic surface that reacts to changes in pressure. The "paint" itself is typically composed of two parts: the oxygen sensitive fluorescent molecule and an oxygen permeable binder. This chapter will serve to introduce the background necessary to understand the development and operation of PSP.

FLUORESCENT MOLECULES

The main element of PSP is the oxygen sensitive fluorescent molecule. Its operation is based on the principle that certain fluorescent molecules are capable of having their fluorescence quenched by the presence of oxygen. Initially, the fluorescent molecule

must be excited by light of a particular wavelength. Typically, this can be light ranging from the UV to red, depending on the molecular structure and environment. When the molecule absorbs photons of light, its electrons are placed in an excited state. It then recovers to the ground state by the emission of photons of light or by radiationless deactivation. In the molecules of interest, oxygen interacts with the excited molecules and the excess energy is transferred to the oxygen in a collisional process, with no photons being emitted. This process, known as oxygen quenching, is the basis for the pressure sensitive paint method. A diagram of this method is shown in Figure 1.1.

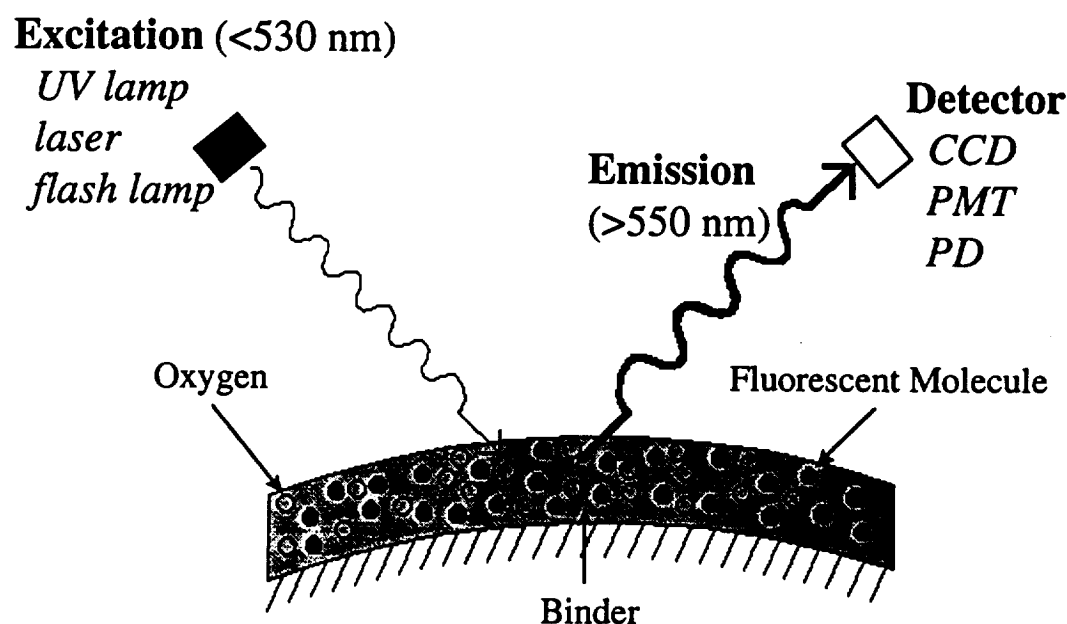


Figure 1.1 General PSP technique

According to Henry's law, oxygen concentration is proportional to the partial pressure of oxygen, and further, the partial pressure of oxygen is proportional to static pressure. Therefore, since the fluorescent molecule is sensitive to oxygen concentration, it is effectively sensitive to the local air pressure. The result is that if there is a locally high pressure area, the fluorescent molecules will more likely be quenched by oxygen.

In these fluorescent molecules, the fluorescent emission is Stokes-shifted so that the excitation and emission wavelengths are separated. This is important for the

application of PSP because it enables the excitation light to be optically filtered from the emission. Figure 1.2 shows the excitation and emission spectra for a typical fluorescent molecule based on ruthenium.⁷

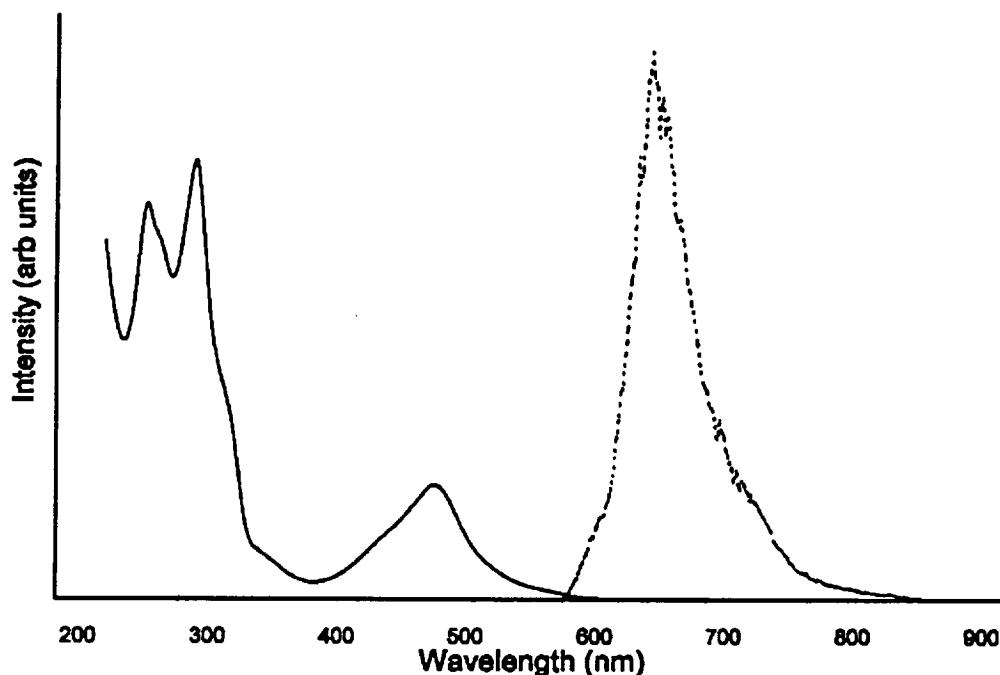


Figure 1.2. Excitation and emission spectra for a ruthenium-based molecule

OXYGEN PERMEABLE BINDER

The other part of the PSP is the oxygen permeable binder. The binder serves two purposes. First, it adheres the fluorescent molecule to the surface of interest. This requires that the binder be robust. Second, it must allow oxygen to reach and interact with the fluorescent molecules. This is important if oxygen quenching is to occur. The oxygen diffusivity of the binder also plays an important role in the time response of the PSP. Thus, the diffusivity of the polymer must be properly chosen to meet the requirements of the particular measurement, i.e. the need for fast or slow time response. The most common type of binder is based on silicon polymers, such as Room Temperature Vulcanizers (RTV). These rubbery compounds make good binders because

of their smooth surface, good oxygen permeability and durability. Silica gel particles are very oxygen permeable and when formed into binders, such as thin layer chromatography (TLC) plates, allow the PSP to be very sensitive. The main disadvantage is that they are not very robust and are sometimes sensitive to changes in humidity. They also exhibit non-linear behavior. The last main type of binder is composed of regular white paint applied to the surface. This is typically Krylon flat white interior paint. The fluorescent molecule, after being dissolved into a solvent, is then sprayed onto the paint. The solvent evaporates, leaving a pressure sensitive layer.

MEASUREMENT TYPES

FLUORESCENT INTENSITY

On a global scale, if oxygen is present in a high concentration, there is a larger probability of radiationless deactivation. Based on Henry's law, an increase in air pressure will result in a proportional increase in oxygen concentration. This process is modeled by the Stern Volmer equation:⁸

$$\frac{I_0}{I} = 1 + K_{sv} P_{O_2} \quad (1.1)$$

I_0 = fluorescence intensity at vacuum conditions

K_{sv} = Stern Volmer constant

P_{O_2} = partial pressure of oxygen

In general, I_0 and K_{sv} are functions of temperature. The version of the Stern Volmer equation shown in equation 1.1 is not very useful in aerodynamic testing. This is because the fluorescence intensity at zero pressure is typically not known due to its dependence on the concentration of fluorescent molecules, paint thickness and illumination intensity. This causes I_0 to be non-uniform across a PSP coated surface. In order to remove the effects of concentration, thickness and illumination variations, the Stern

Volmer equation can be rewritten as a ratio of intensity at some known condition with the intensity at the test condition:

$$\frac{I_{\text{ref}}}{I} = A(T) + B(T) \left(\frac{P}{P_{\text{ref}}} \right) \quad (1.2)$$

I_{ref} = fluorescence intensity at reference condition

P_{ref} = pressure at reference condition

$A(T), B(T)$ = Stern Volmer constants

The result is that an increasing pressure causes the intensity of the paint to decrease. In using equation 1.2, an intensity map must be acquired at a reference condition, typically a flow off or slow rotation where the pressure is a known constant across the surface. While this version of the Stern Volmer relation is much more useful than that given in equation 1.1, another problem occurs. If the flow on and flow off images become misaligned due to model movement or rotation, a significant amount of noise and errors are introduced into the intensity ratio. Much work has been done in this area of image registration to compensate for model or system misalignment.⁹

In this version of the Stern Volmer equation, the constants A and B are written as functions of temperature. Figure 1.3 shows Stern Volmer curves for various paints at room temperature. A calibration of Ru(ph₂-phen) in GE RTV 118 at several temperatures is given in Figure 1.4. The Stern Volmer constants can be written in the following form¹⁰:

$$A(T) = a_1 \left[1 + \frac{E_{\text{nr}}}{RT_{\text{ref}}} \left(\frac{T - T_{\text{ref}}}{T_{\text{ref}}} \right) \right], \quad B(T) = b_1 \left[1 + \frac{E_p}{RT_{\text{ref}}} \left(\frac{T - T_{\text{ref}}}{T_{\text{ref}}} \right) \right] \quad (1.3)$$

E_{nr} = non-radiative activation energy

E_p = polymer activation energy

R = interaction distance

a_1, b_1 = constants

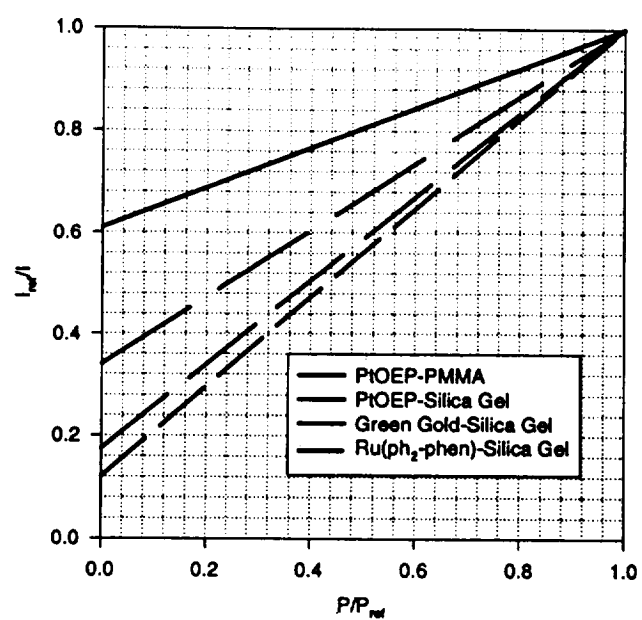


Figure 1.3. Stern Volmer curves of various PSPs.

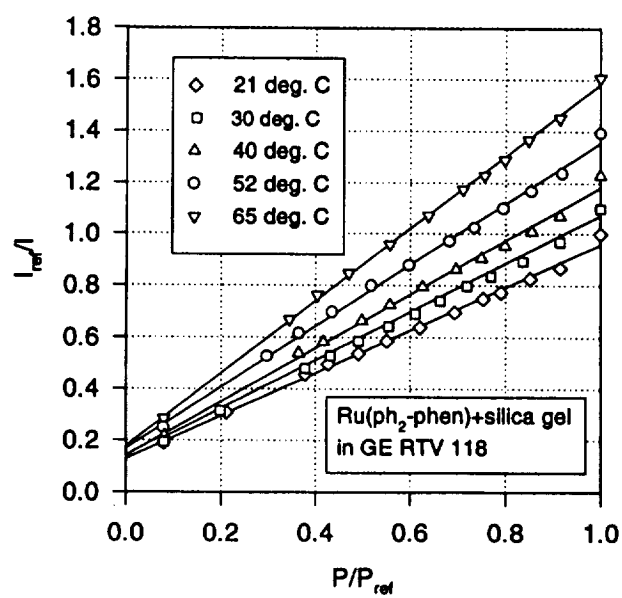


Figure 1.4. Pressure-temperature calibration of Ru(ph₂-phen)

FLUORESCENT LIFETIME

In addition to intensity, the fluorescence lifetime of an oxygen sensitive molecule is also a function of pressure and temperature. Fluorescence lifetime is defined as the time it takes for molecular emission to die out once the excitation source is removed. Similar to intensity, the Stern Volmer equation can be written in the following form for fluorescence lifetime:

$$\frac{\tau_{\text{ref}}}{\tau} = C(t) + D(t) \left(\frac{P}{P_{\text{ref}}} \right) \quad (1.4)$$

τ_{ref} = fluorescence lifetime at reference condition

$C(t), D(t)$ = Stern Volmer constants

As shown in Equation 1.4, an increasing pressure will decrease the fluorescence lifetime. The advantage to using lifetime is that, theoretically, it is not sensitive to changes in concentration, thickness or illumination intensity. Therefore, once a calibration is done, one only needs to know the lifetime at one particular pressure, eliminating the need for a reference map of the lifetime on the surface. This is very advantageous when starting and stopping a wind tunnel becomes time consuming, or when reference conditions are very difficult to get, such as with rotating machinery. A lifetime calibration of Ru(ph₂-phen) in GE RTV 118 with added silica gel particles is shown in Figure 1.5.¹¹

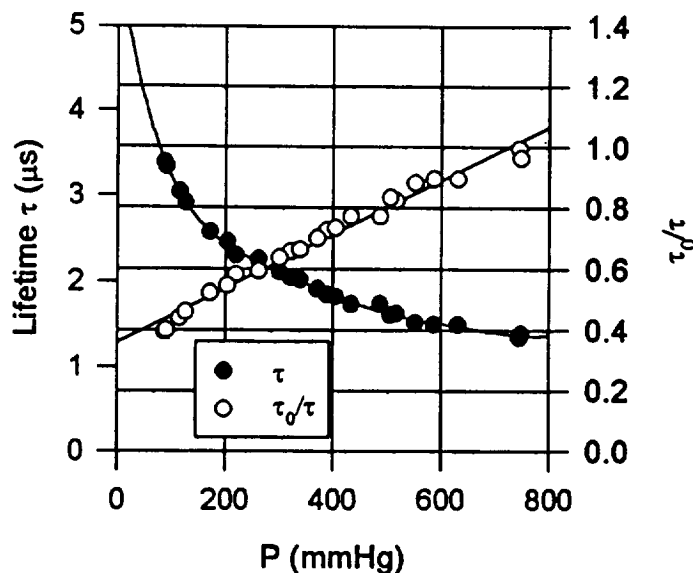


Figure 1.5. Lifetime calibration of Ru(ph₂-phen)

TEMPERATURE SENSITIVITY

Unfortunately, pressure sensitive paints are also sensitive to temperature. A rise in temperature will increase the probability that the molecule will transition back to the ground state by a radiationless process. This process is known as thermal quenching. Temperature sensitivity can lead to many problems in converting the intensity distributions to pressure if not taken into account. Therefore, a PSP must have its temperature effects characterized and corrected, or be used in an isothermal environment for it to be effective. This problem is especially apparent in low speed tests where pressure changes are small and temperature drifts due to the local environment can cause intensity changes on the order of or greater than the pressure dependent intensity changes.

The binder chosen can also have a large effect on the PSP's temperature sensitivity.¹² This binder-related temperature effect can come from either fluorescent molecule/binder interactions or the temperature-dependence of oxygen diffusivity. The latter has been demonstrated to be a major part of the temperature sensitivity of the silicone rubber PDMS. Clearly, the binder chosen to go with a particular fluorescent

molecule is not based solely on its oxygen permeability and robustness. All sources of temperature sensitivity must be taken into account in order to minimize temperature effects on PSP.

PRESSURE SENSITIVE PAINT DEVELOPMENT

The standard pressure sensitive paint that is used in this research is bathophen ruthenium chloride in General Electric RTV 118. The ruthenium-based paints exhibit strong fluorescence, good photo-stability, comparatively low temperature effects and are compatible with readily available blue and green excitation sources such as argon ion lasers and green solid state lasers. As with most fluorescent molecules, they can also be easily excited by UV light. Temperature sensitivity is about -0.78% intensity change per degree C. Typical paint preparation begins by dissolving 3 mg of bathophen ruthenium chloride, obtained from GFS Chemicals, in 50 ml of dichloromethane. Fifteen ml of GE RTV 118 is then added and mixed for 5 minutes. This PSP can then be applied directly to the aerodynamic surface by spraying with a paint gun. For more convenience, the paint can be sprayed onto white monocoat (model airplane covering) so that the paint can be prepared ahead of time and applied to the surface as a tape.

Another typical pressure paint is based on a mixture of platinum meso-tetra (pentafluorophenyl) porphine (PtTFPP), obtained from Porphyrin Products, in either polystyrene or model airplane dope. PtTFPP is very oxygen sensitive, but typical of most porphines, it suffers from large temperature effects and severe photodegradation. This paint's temperature sensitivity is about -1.8%/°C. It is made by first dissolving 2 g of polystyrene in 40 ml of toluene, which can be accelerated by the addition of heat. About 3 mg of PtTFPP is then added to make the PSP. Paint application is the same as illustrated above for the ruthenium paint.

The properties of these two pressure paints, as well as several others, are shown in Table 1.1. One interesting paint is green gold (perylene dibutrate) on TLC plates. It has a

positive temperature coefficient, meaning that its intensity increases as temperature increases. This is due to its different photo-physical processes. This property makes it a potentially useful pressure paint where temperatures are significantly increased over the reference, such as in jet engine compressor blades. Unfortunately, green gold has not been shown to be pressure sensitive in binders other than TLC plates.

Table 1.1. Properties of various pressure paints

Paint/Binder	λ_{ex} (nm)	λ_{em} (nm)	Stern Volmer A,B @ 23 °C	Lifetime @P _{atm}	Temp sensitivity (%/°C)	a ₁ ,b ₁ (eq. 1.3)	E _{ex} /RT _{ref} , E _p /RT _{ref} (eq. 1.3)
Ru(ph ₂ -phen)/ RTV118	337, 457	600	0.27, 0.75	1.3μs	-0.78	0.13, 0.87	2.82, 4.32
Ru(ph ₂ -phen)/ TLC	337, 457	600	0.17, 0.84	4.7μs			
PtTFPP/ dope	390, 514	650	0.43, 0.60	50μs	-2.3		
PtTFPP/ TLC	390, 514	650	0.27, 0.72	50μs	-2.1		
PtTFPP/ white paint	390, 514	650	0.32, 0.68	50μs	-1.5		
green gold/ TLC ⁶	UV, 457	520	0.33, 0.67	12.8ns	4.5		

CHAPTER 2 : MEASUREMENT SYSTEMS

As outlined in Chapter 1, there are two different types of measurements possible when using PSP, intensity and lifetime. Both are acquired in similar manners. First the paint is excited, and then the fluorescence intensity or lifetime is measured. There are also two main methods of acquiring these pressure-dependent changes. They consist of the CCD technique and the laser scanning technique. Both methods have inherent advantages and disadvantages. This Chapter will serve to introduce the two methods and describe the laser scanning system for use with intensity and lifetime measurements in detail.

CCD BASED

Currently, the most common way to gather experimental data from pressure sensitive paints is to illuminate the experiment with blue or UV lamps, and then acquire and digitize the fluorescent emission with a CCD camera and a PC based frame digitizer board. This digitized image is then processed to get the pixel intensities. After the flow-off image is divided by the flow-on image to remove non-uniform lighting and paint effects, the ratio can be converted to pressure readings by the use of calibration curves. This gives a pressure map of the entire surface. A typical CCD based data acquisition system is shown in Figure 2.1.

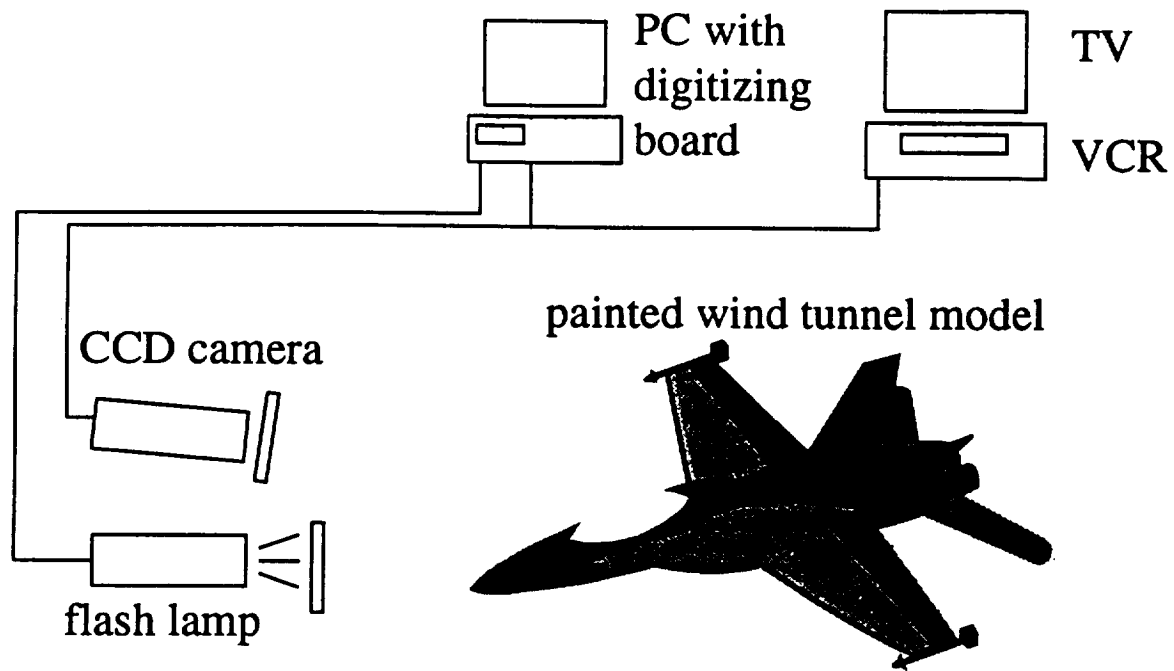


Figure 2.1. CCD data acquisition method

Standard CCD arrays are usually limited to 8 bit resolution and 640x480 pixels. Cooled, scientific grade CCD arrays with resolutions up to 16 bit are available. Although these units have much better signal-to-noise ratios, they are typically expensive. One problem involved in the CCD method is that the model must be uniformly illuminated each time an image is acquired in order to minimize errors in the intensity-to-pressure conversion. If the excitation light varies in intensity, fluorescence will also vary, resulting in overall shifts in calculated pressure from one test to the next. Most importantly, model movement can cause displacement between the flow-off and flow-on images, requiring image mapping and spatial transformations. This is very important because often individual pixels vary in gain from those around it, resulting in noise if the flow off and flow on images are not aligned correctly.

LASER SCANNING

An alternative to the CCD method that improves upon the pressure resolution and noise characteristics is the laser scanning system. In this technique, a focused laser spot is used to excite the paint while a low noise photo-detector (photo-multiplier tube or photo-diode) measures the emission intensity or fluorescence decay of the paint. After being amplified and filtered, a high resolution A/D converter digitizes the signal. An intensity or lifetime map is created by scanning the spot across the test surface using a computer controlled scanning mirror. The map is then converted to pressure from the calibration data for the particular paint. Computer control of the laser spot allows the resolution and scan area to be user-specified, permitting non-rectangular, variable density grids. This is advantageous when the user wants to measure the pressure in an area of high pressure gradients with high spatial resolution. The use of a laser provides more uniform illumination than lamps, while intensity variations can be easily monitored and corrected. A basic laser scanning system is shown in Figure 2.2.

The laser scanning system is easily adaptable for use in intensity measurements as well as lifetime based measurements. Model preparation and setup is the same, while just a few changes in instrumentation are needed. In addition to intensity and lifetime, there is another type of PSP measurement utilizing two-color paints. The following sections will detail these measurements using the laser scanning system.

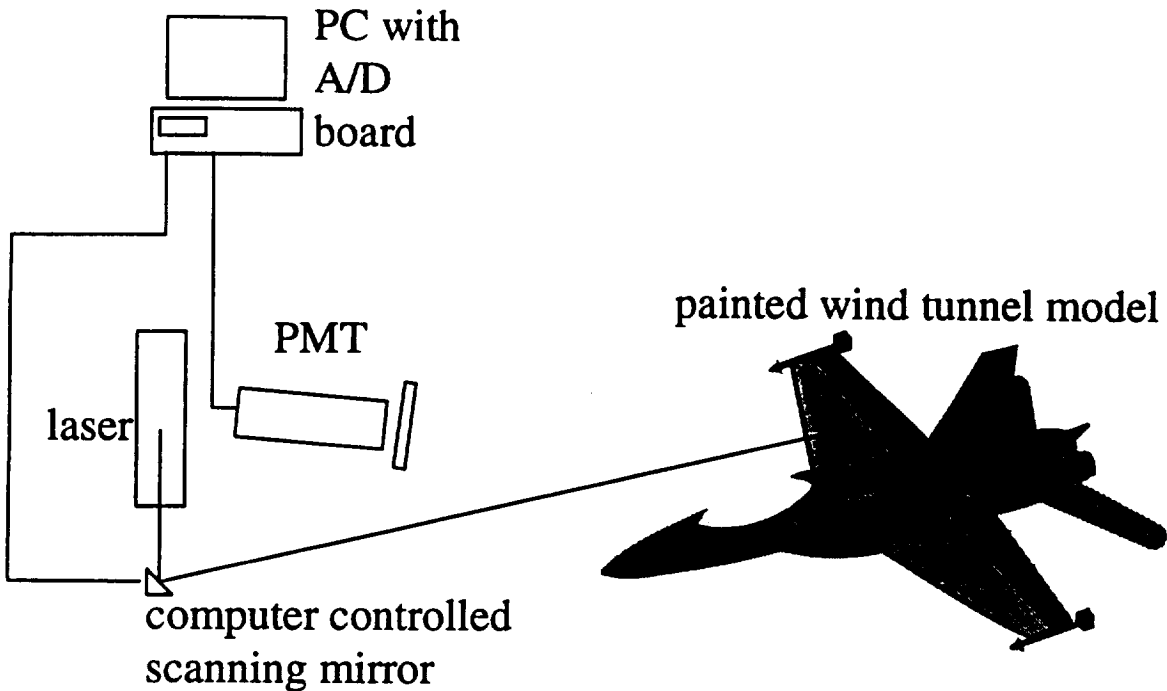


Figure 2.2. Basic laser scanning system

INTENSITY BASED

Low speed wind tunnel tests require the measurement of pressure changes on the order of 0.01 psi, which corresponds to a 0.3%-0.6% intensity change for typical pressure paints at atmospheric conditions. Accurately measuring this small change means increasing the signal-to-noise ratio (SNR) to as high a level as possible. Assuming shot noise limited detection using a photomultiplier tube, the SNR is given by equation (2.1):¹³

$$SNR = \sqrt{\frac{\eta P_s}{h\nu B}} \quad (2.1)$$

η = detector quantum efficiency

P_s = optical power incident on the PMT

h = Planck's constant

ν = optical frequency

B = electrical bandwidth of the detection electronics

Therefore, increasing the SNR means either increasing the fluorescence or decreasing the electrical bandwidth. Increasing the fluorescence can be done by increasing the laser power or increasing fluorescent molecule concentration, but care must be taken to not photodegrade the paint or increase the concentration to levels that cause the paint to self-quench. An easier way to increase the signal-to-noise ratio is to use a lock-in amplifier. With a lock-in amplifier, the bandwidth can be decreased to well below 1 Hz.¹⁴ This is accomplished by first modulating the laser. The lock-in is then set to only be sensitive to the part of the signal from the PMT that is at the modulation frequency. All other parts of the signal are filtered out, greatly reducing the noise content.

LIFETIME BASED

Two different methods are available to use fluorescent lifetime in pressure measurements. Lifetime can be measured directly by first modulating the intensity of the laser in a pulse or square wave pattern. Fluorescence decay curves are recorded and averaged with a digital oscilloscope or A/D board. An exponential curve is then fit to the data and the lifetime calculated (Figure 2.3). Fitting a curve to the data at each surface data point requires much computing time and requires a fast A/D board (~10 MHz for typical $\tau=1\mu\text{s}$). A lifetime calibration for Ru(ph₂-phen) was shown in Figure 1.5.

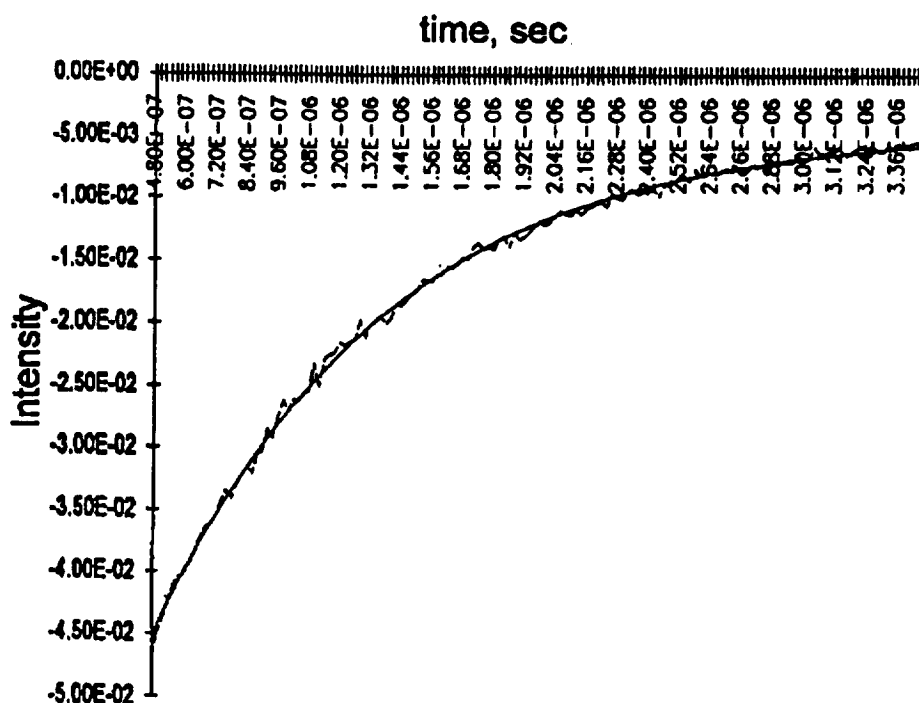


Figure 2.3. Fluorescence intensity decay curve

A similar method is to again intensity modulate the incident laser light, but then measure the phase shift between the excitation and fluorescence signals (Figure 2.4). Since there is a finite time associated with the excitation and subsequent emission in the molecule, the excitation and fluorescence signals will be out of phase if the modulation frequency is chosen properly. Because this phase shift is related to the lifetime, theoretically it will still be independent of concentration and lighting effects, so no flow-off scan is needed. Assuming a first order system, the phase angle is related to the lifetime by the equation:

$$\tan(\phi) = \tau\omega \quad (2.2)$$

ϕ = phase angle

ω = modulation frequency

The phase angle is measured by a lock-in amplifier and read by a computer with an A/D board. One major advantage to this method is that because we are measuring AC

and not DC signals, the noise attributed to outside conditions (60 Hz line noise, background lighting, etc.) does not affect the measurement of the phase angle. An in-situ phase calibration plot for Ru(ph₂-phen) in GE RTV 118 is shown in Figure 2.5.

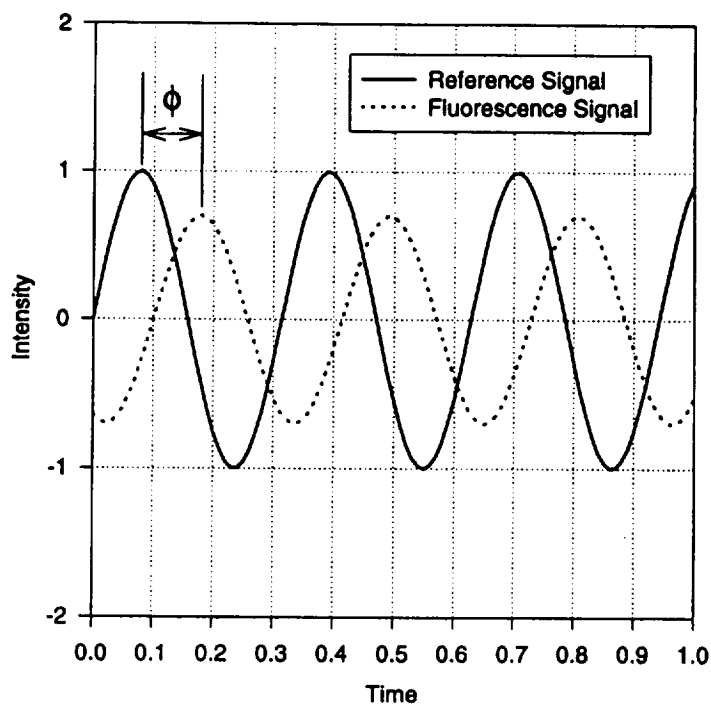


Figure 2.4. Phase measurement method

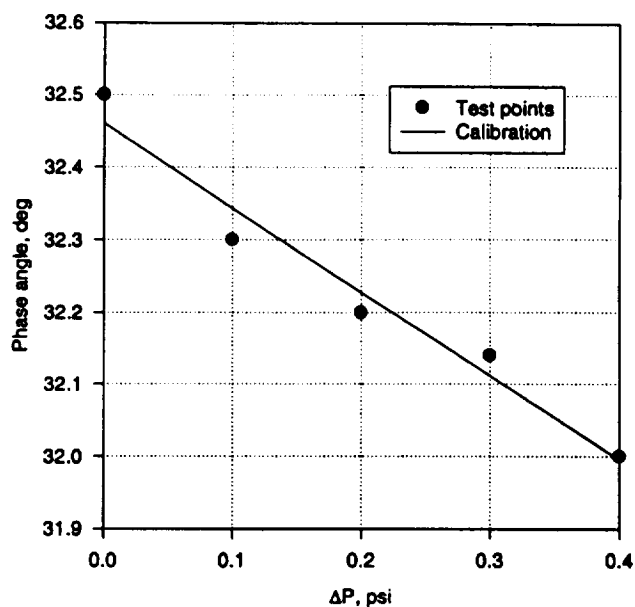


Figure 2.5. Phase calibration for Ru(ph₂-phen) in GE RTV 118

To maximize the potential of the phase measurement technique, a careful selection of the modulation frequency is necessary to obtain the maximum sensitivity of pressure change to phase angle. A simple analysis reveals that $\tau\omega=1$ (and thus $\phi=45^\circ$) for this condition.¹⁵ Noting that $\omega=2\pi f$ where f is the modulation frequency in Hz, the maximum sensitivity modulation frequency is:

$$f = \frac{1}{2\pi\tau} \quad (2.3)$$

A plot of the maximum sensitivity frequency for a range of lifetimes is shown in Figure 2.6. For $\tau=1\mu\text{s}$, typical of fast ruthenium complexes, the modulation frequency is about 160 kHz. For PtTFPP, with $\tau=80\mu\text{s}$, the modulation frequency becomes 2000 Hz. For modulation frequencies above 6000 Hz, acousto-optic or electro-optic modulators are needed. Below 6000 Hz, rotating optical choppers work well. Figure 2.7 shows the

actual phase difference between atmospheric and nitrogen conditions for PtTFPP versus modulation frequency. The maximum difference occurs at 1700 Hz, close to the predicted frequency. The intensity, however, decreases as the modulation frequency increases, as shown in Figure 2.8. This not only decreases the intensity SNR (see Eq. 2.1), but also decreases the phase SNR. In a simple analysis, Holavanahali, et. al. found that the noise in the phase measurement is related to the intensity SNR by equation 2.4.¹⁶ The result is that the modulation frequency used must be a balance of phase change and fluorescence intensity in order to achieve good results.

$$\phi_M = \phi + \frac{1}{SNR} \quad (2.4)$$

ϕ_M = measured phase in radians

ϕ = actual phase

SNR: from equation 2.1

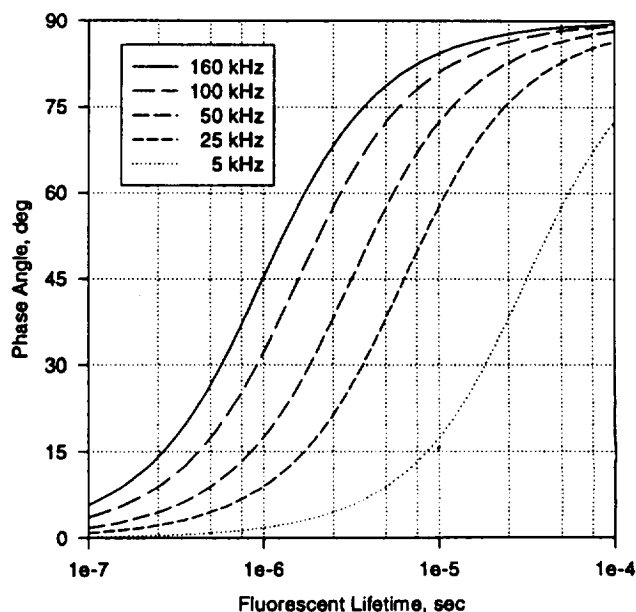


Figure 2.6. Phase angle measurements for various modulation frequencies

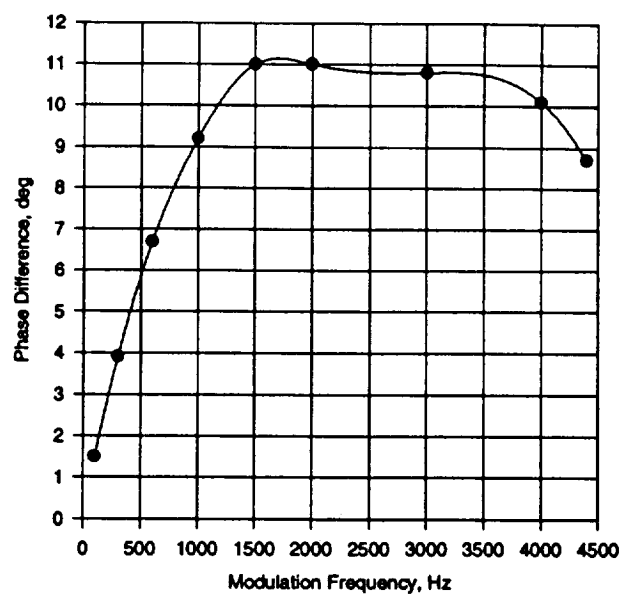


Figure 2.7. Phase difference between atmospheric and nitrogen conditions using PtTFPP

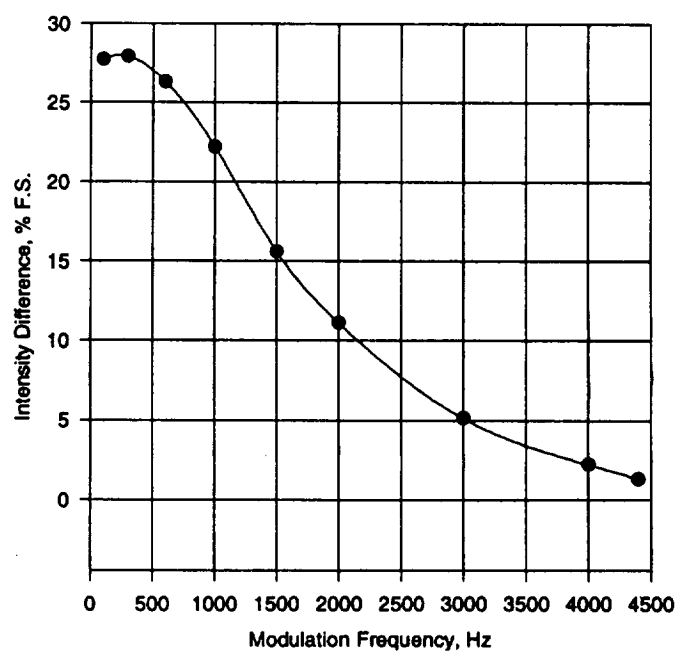


Figure 2.8. Intensity difference between atmospheric and nitrogen conditions using PtTFPP

TWO COLOR PAINT

Two-color paint is composed of a pressure sensitive luminophor along with a pressure and, ideally, temperature insensitive reference luminophor. The probe luminophor and reference luminophor are excited by the same illumination source, while their emission spectral bands are separated enough to be resolved by two different band-pass filters. If the materials are evenly distributed throughout the paint, the advantage is that a flow off reference would not be needed, since the reference intensity is provided by the pressure insensitive luminophor. Ideally, it is also independent of changes of concentration and coating thickness. Another use of two-color paint is to use a temperature sensitive reference luminophor to provide a temperature distribution for the pressure calibration. In using the paint this way, a flow off scan is still needed, but having easily generated temperature corrections is a significant advantage.

CHAPTER 3 : LOW SPEED EXPERIMENTS

The objective of the research presented in this chapter is to develop a system that is capable of measuring pressure in low speed environments. Several tests will be described which illustrate the effectiveness of the laser scanning system and the different techniques that can be utilized to improve accuracy and resolution.

JET IMPINGEMENT

A low speed impinging jet test is used to demonstrate the increase in signal-to-noise ratio of the laser scanning system combined with optical chopping and lock-in amplification. These experiments will determine the ultimate pressure resolution and accuracy available with this system because of the tightly controlled test conditions available in the lab. The experimental setup used is shown in Figure 3.1. Pressure sensitive paint is coated on the impinging surface, while a 5 mm diameter nozzle is placed 10 mm from the plate. Paint excitation is provided by an argon ion laser with the 457, 488 and 514 nm lines, while an optical chopper modulates the beam. A 0.2 mm laser spot is scanned across the plate. The luminescence is detected using a low noise photomultiplier tube that has an integrated current to voltage converter with a 600 nm high-pass filter to only pass the fluorescence. The signal is then input into a lock-in amplifier. The lock-in output is then sampled with a PC.

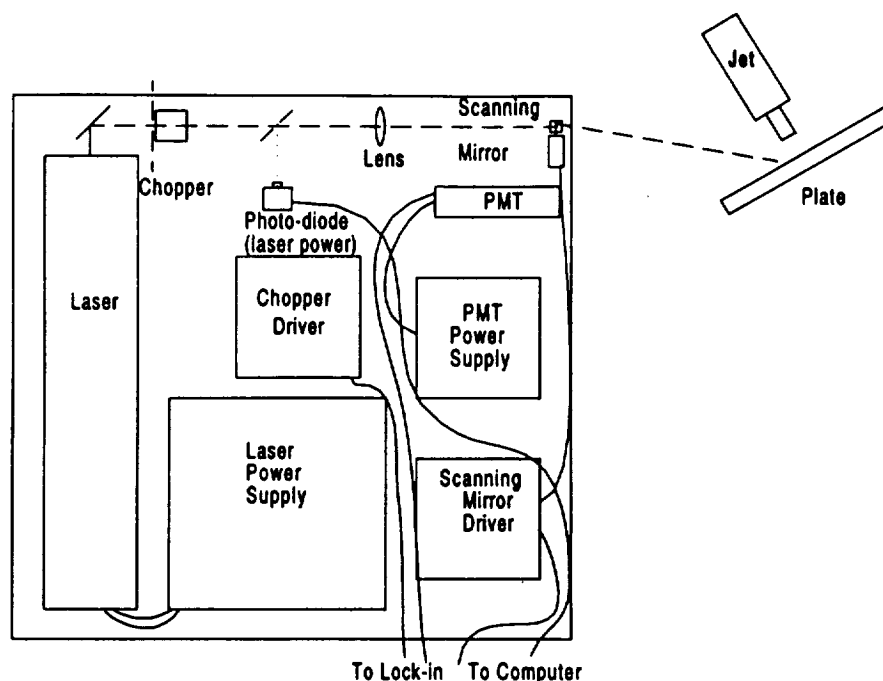


Figure 3.1. Jet impingement setup

INTENSITY-BASED MEASUREMENTS

In the first tests, a Ruthenium-based PSP from McDonnell Douglas was used. The lock-in output was sampled with a 12-bit A/D board. The pressure distribution was found using an in-situ calibration of the paint. The raw pressure data taken is shown in Figure 3.2 and indicates the noise level of the measurement system. Note that the signals were ensemble averaged over 10 scans. This data was then filtered numerically, with the resulting distribution compared to pressure tap data in Figure 3.3. The pressure paint agrees well with the taps at all pressures. Compared with previous measurements in the same flow conditions, the results thus far have shown that large signal-to-noise improvements can be made by the use of optical chopping and lock-in amplification.¹⁷ Without the use of a lock-in amplifier and optical chopper, it has been shown that measurements of less than 1 psi had signal-to-noise ratios on the order of 1, no matter how many ensembles are averaged.¹⁸ These signal improvements have enabled the measurement of low pressures (< 1 psi) with good resolution.

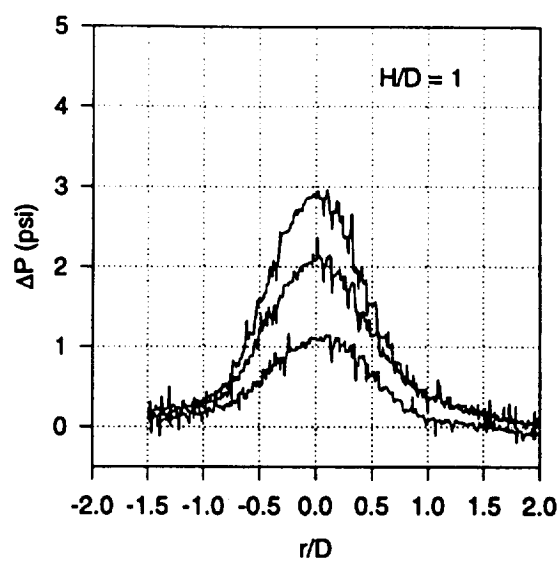


Figure 3.2. Pressure distributions obtained without filtering

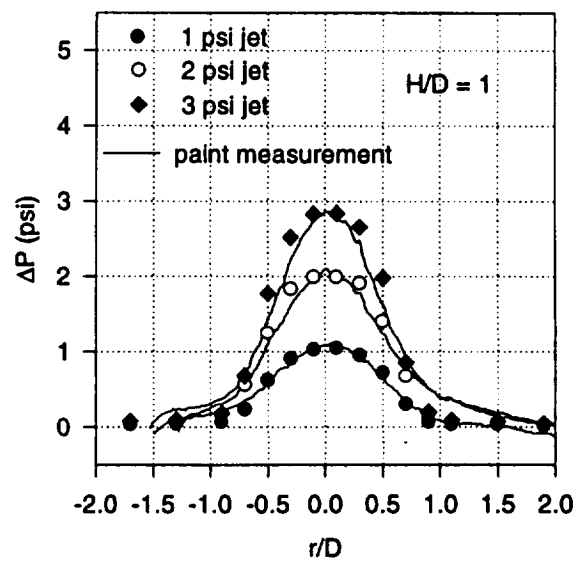


Figure 3.3. Filtered PSP pressures compared to tap data

Further refining of this system is made by directly connecting the computer and the lock-in amplifier by the use of a general purpose interface bus (GPIB) connection, eliminating the noise associated with the A/D conversion. This allows data to be sampled internally by the 16 bit A/D contained in the lock-in. The first paint used is Ru(ph₂-phen) in GE RTV 118. The chopping frequency is 500 Hz with a lock-in time constant set to 200 ms. Five ensemble scans are averaged. Figure 3.4 shows the raw intensity distributions of the paint over a range of jet total pressures from 0.05 to 0.4 psid. The dip in the middle is from the jet partially blocking the reflected fluorescence. The ratioed signals (I_{ref}/I) are shown in Figure 3.5. The deviation of the intensity ratio from unity at large x/d indicates temperature effects at different total pressures. The noise level is significantly lower than that shown in Figure 3.2. Also note that ratioing removes the effects of the uneven fluorescence signal from Figure 3.4. Based on in-situ calibration, the pressure distributions can be obtained and are shown in Figure. 4.6. This illustrates that the ruthenium based paint is capable of measuring pressures below 0.05 psi with relative accuracy and having resolutions better than 0.01 psi.

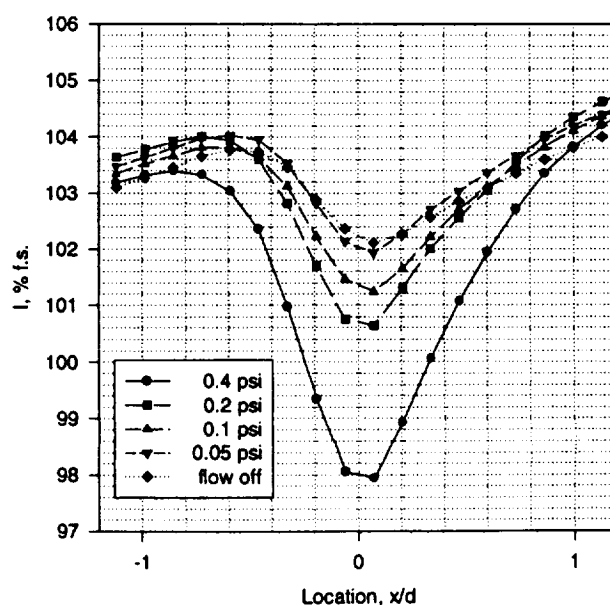


Figure 3.4. Raw intensity signals using ruthenium

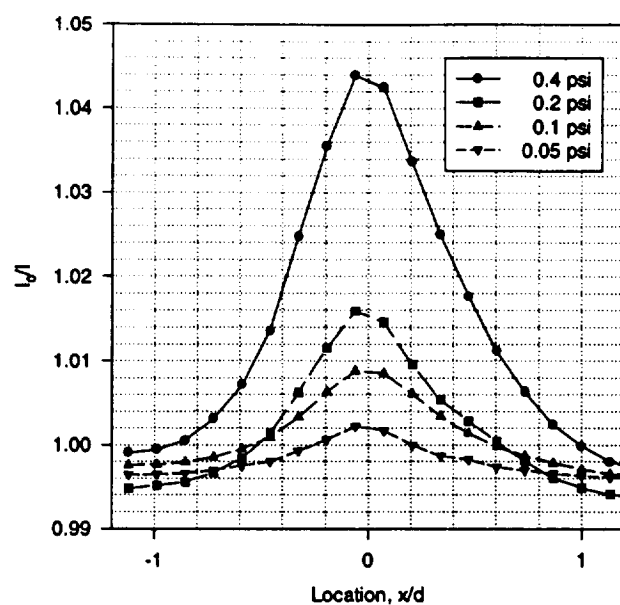


Figure 3.5. Ruthenium intensity ratios

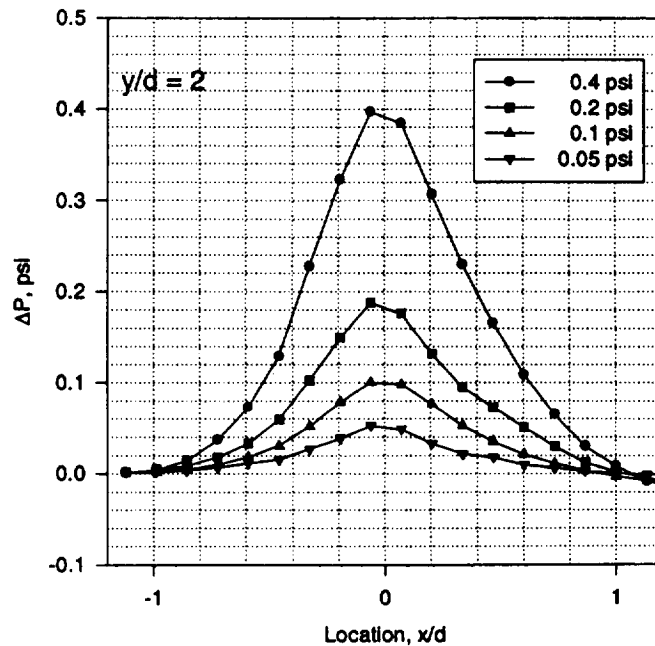


Figure 3.6. Ruthenium intensity-based pressure

The second paint used is Platinum meso-Tetra (Pentrafluorophenyl) Porphine (PtTFPP) in model airplane dope. For this paint, the raw relative intensity and pressure distributions are shown in Figures 4.7 and 4.8, respectively. In all of the data using PtTFPP, there are dips aside the stagnation pressure peaks. These anomalous features are due to the temperature effects of the paint, since the jet and ambient air are not isothermal. Similar behavior of intensity distributions was also observed for PtOEP-GP197 paint.¹⁷ PtTFPP-dope paint has a high temperature sensitivity, with the temperature coefficient being $-2.3\%/^{\circ}\text{C}$ compared with $-0.78\%/^{\circ}\text{C}$ for $\text{Ru}(\text{ph}_2\text{-phen})$ in GE RTV 118.

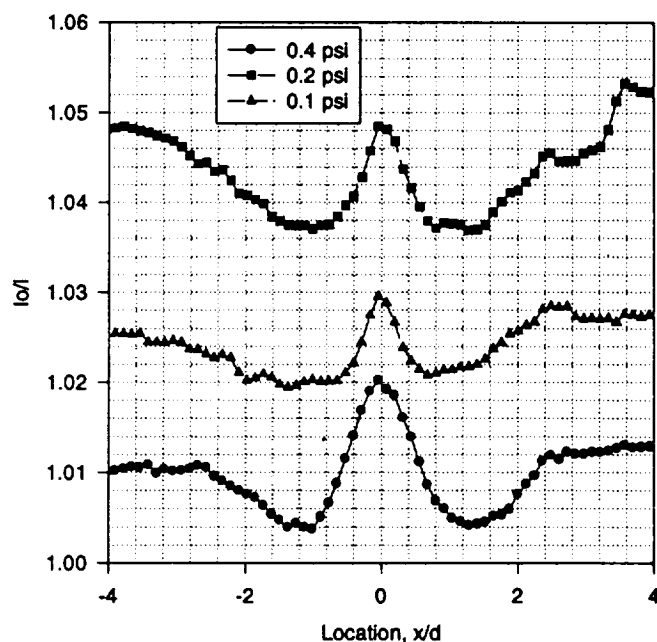


Figure 3.7. PtTFPP intensity ratio

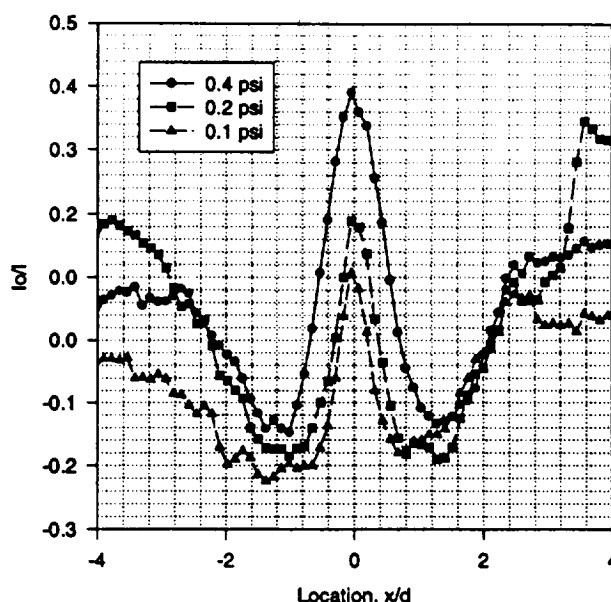


Figure 3.8. PtTFPP intensity-based pressure

PHASE-BASED MEASUREMENTS

Theoretically, luminescent lifetime is an intrinsic property of the probe molecule and not dependent on illumination intensity, concentration, and paint thickness. This leads to the capability of making pressure measurements without needing a reference intensity map for the flow-off/flow-on ratios. It is also generally believed that lifetime/phase methods are independent of luminophor concentration. Both of these advantages will result in easier and possibly more accurate pressure measurements. Here, the feasibility of the phase-based technique for pressure measurement in low speed flows is examined.

For Ru(ph₂-phen) in GE RTV 118, an acoustic-optic modulator was used instead of the mechanical chopper since high modulation frequency is needed for this paint, which has a lifetime of about 2 μs in ambient conditions. In the tests, the modulation frequency was set at 80 kHz. Figure 3.9 shows raw phase distributions in flow-off condition and total pressures of 0.1, 0.25 and 0.4 psid. The phase change produced by impinging jet can be easily seen. Theoretically speaking, the phase in the flow-off case should remain

constant, since the surface pressure is at constant ambient pressure. Surprisingly, the phase in the flow-off case varies considerably over the scanning range. The spatial phase pattern is repeatable at a fixed scanning position. This indicates that the pattern is related to the paint coating. Hartmann, et. al. observed similar results and attributed it to the microheterogeneity of the polymer environment. They observed that in solution, where each molecule exists in the same environment, the fluorescent molecule exhibits linear Stern-Volmer plots and single exponential decay. When immobilized in a solid matrix, such as a polymer, the nature of the matrix is no longer the same on an averaged time scale for all molecules. This results in altered luminescence and quenching behavior.¹⁹ Similar results are shown by James, et al. and Liu, et al.^{20,21}

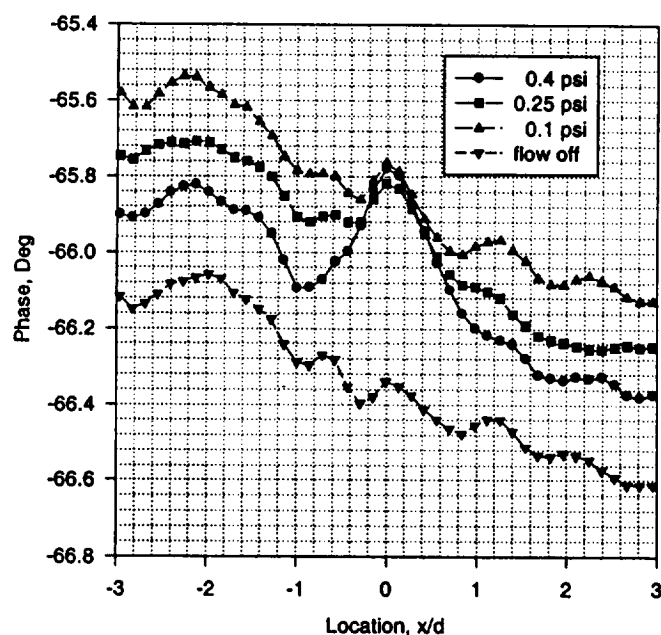


Figure 3.9. Ruthenium phase distributions

In Figure 3.9, the variation for the flow-off case is about 0.5 degrees. The small phase variation may be not significant for measurements in high speed flow where the pressure change is large, as will be demonstrated in the transonic wing test. However, in low speed flows, this variation can introduce considerable errors in the pressure

measurement. In order to correct the phase variation, the raw phase distribution in the flow-off conditions is subtracted from the flow-on phase distributions. While this negates the benefits associated with lifetime/phase measurements, it allows the current data to be reduced.

The corrected phase distributions are shown in Figure 3.10. The reasons for the shift in the phase baseline at different pressures are unclear, but may be due to temperature or humidity effects. Figure 3.11 shows the pressure distributions after the shift is removed. The in-situ calibration used was given in Figure 2.7. The noise level in the phase detection is higher, and accuracy lower, than in the corresponding intensity detection.

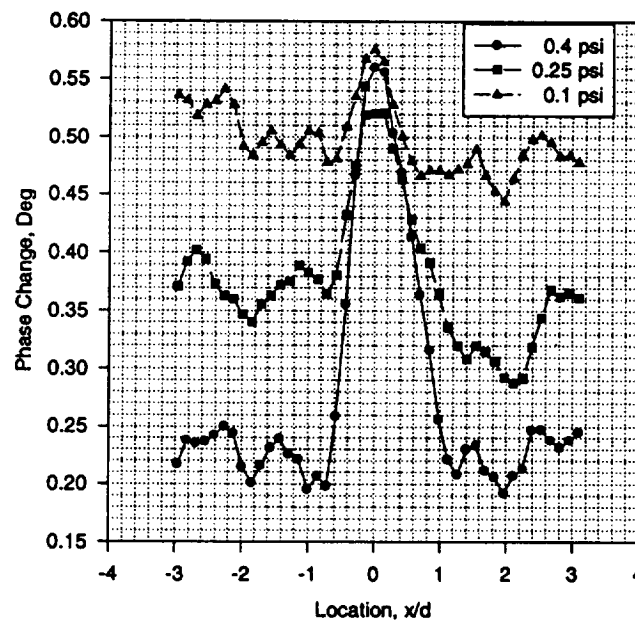


Figure 3.10. Ruthenium phase with flow-off subtracted

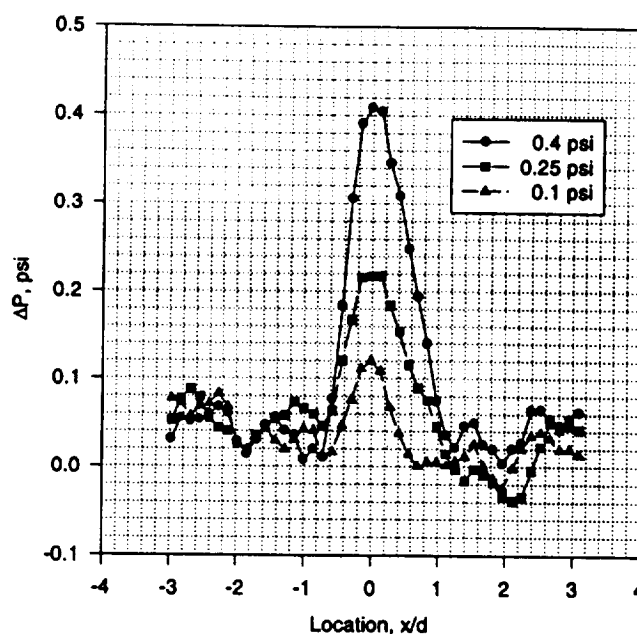


Figure 3.11 Ruthenium phase-based pressure

Phase measurements were also made using PtTFPP in dope. The modulation frequency was set at 1.5 kHz since the lifetime of PtTFPP in dope is about 50 μ s in ambient conditions. Figures 3.12 and 3.13 show the phase distributions from which the flow-off phase variations are subtracted and pressure distributions converted. Obviously, the trend of the pressure distributions is not correct. The dips in the phase profiles correspond to those in the intensity distributions in Figure 3.7. The high temperature sensitivity of PtTFPP-dope paint severely limits the effectiveness of its use for pressure measurements, unless temperature corrections are used or the flow is isothermal.

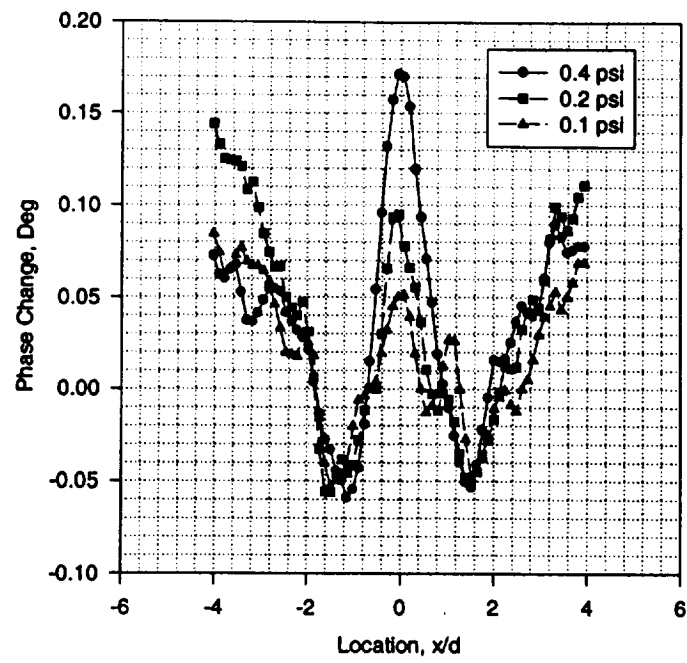


Figure 3.12. PtTFPP phase distributions

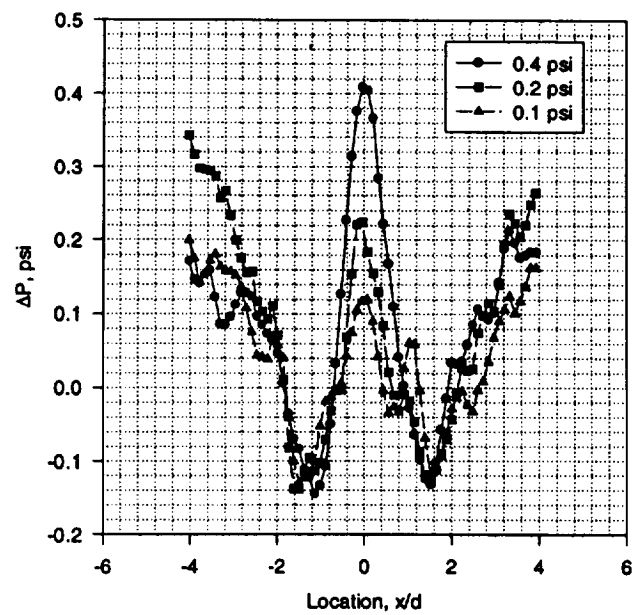


Figure 3.13. PtTFPP phase-based pressure

Fluorescent Molecules in Solution

To investigate the non-uniform phase distributions found in the flow-off cases, tests of fluorescent molecules in solution were conducted. It was believed that the silicon rubber-based binder was interacting with the fluorescent molecules, causing the non-constant phase. Bathophen ruthenium chloride was dissolved into toluene and placed in a glass dish. One end of the dish was elevated, producing a solution that was deeper at one end. Intensity and Phase distributions at two different slopes, 5° and 10° , were taken determine if the phase would remain constant in a solution as theorized. Data was collected using a lock-in amplifier, with both phase and intensity being recorded. The results for the phase distributions are shown in Figure 3.14, while intensity is shown in Figure 3.15. For the 5 degree slope data, no averaging was done. The 0.06 variation in phase effectively amounts to a 0.05 psi error for this fluorescent molecule, much lower than the 0.6° variation shown in Figure 3.9. For the 25° slope, 100 averages at each point were conducted. As expected, the noise in the averaged signal has reduced, and the distribution is nearly constant within experimental error. Therefore, the problems with an uneven phase distribution in polymer-based paints shown earlier are not due to variations in the fluorescent molecules themselves, but interaction of the polymer, fluorescent molecule and environment.

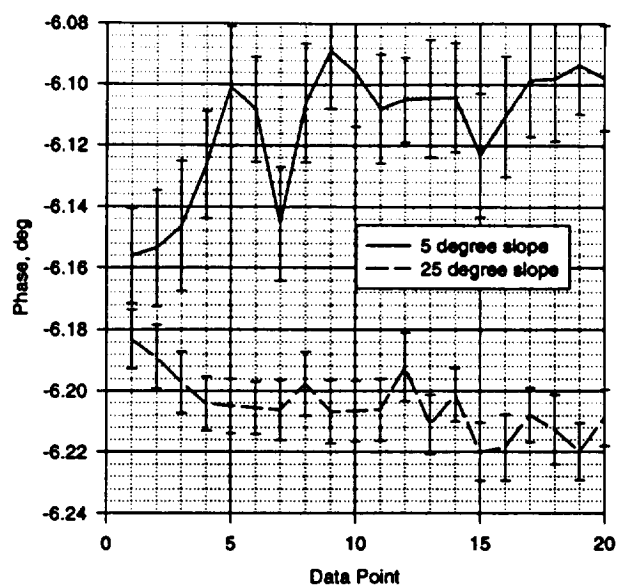


Figure 3.14. Phase distribution in a sloped fluorescent solution

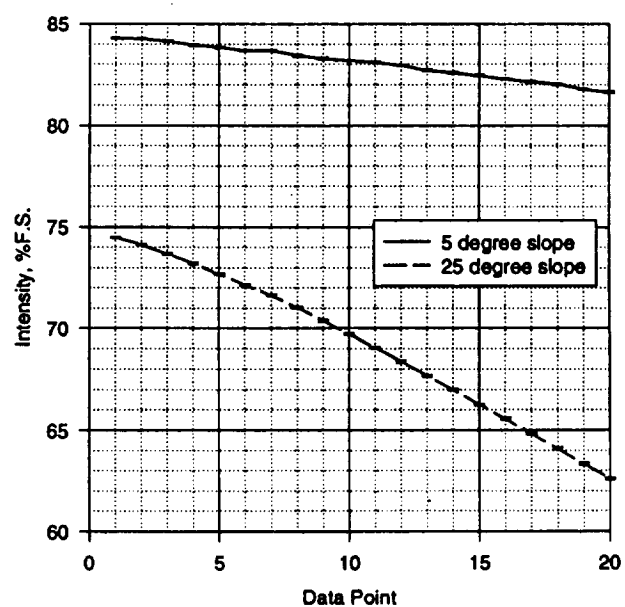


Figure 3.15 Intensity distribution in a sloped fluorescent solution

TWO-COLOR PAINT MEASUREMENTS

In this section, a two-color paint for pressure measurement in low speed flow is examined. The two-color paint used is PtTFPP/Green Gold in dope that is adapted from the formulation given by Oglesby et al.²² Green Gold gives non-pressure dependent luminescence emission in the range of 450 to 600 nm. The pressure dependent emission of PtTFPP is centered at 650 nm. Intensity ratio of 650 nm emission with 550 nm emission is a function of pressure and is independent of illumination and coating thickness. The two-color paint was excited by all lines of an Argon laser. A band-pass filter (550 ± 40 nm) was used for Green Gold and another band-pass filter (650 ± 40 nm) for PtTFPP. The data for each wavelength band was taken on separate runs, with the filters being rotated onto a single PMT. Figure 3.16 shows raw intensity distributions of 550 nm (reference) and 650 nm (pressure sensing) in both flow-on (0.5 psid) and flow-off conditions. It is found that the pattern of the 550 nm intensity, I_{550} , does not match the 650 nm intensity, I_{650} , even in the flow-off condition. Thus, as shown in Figure 3.17, the ratio between $(I_{650})_0$ and $(I_{550})_0$ is not constant over a scanning range, where the subscript 0 denotes the flow-off condition. This illustrates that the two luminophores are not perfectly mixed in the binder, which results in a two-color paint that doesn't have the ability of being used without a flow-off scan.

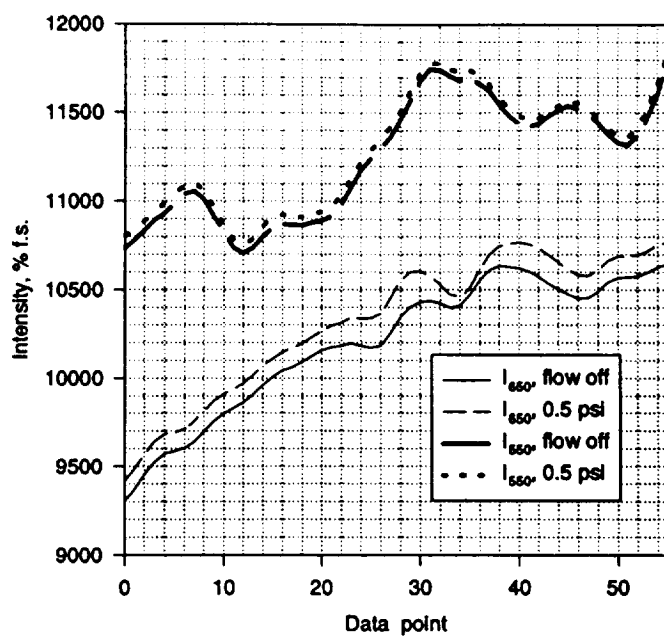


Figure 3.16. Two-color paint red and green traces

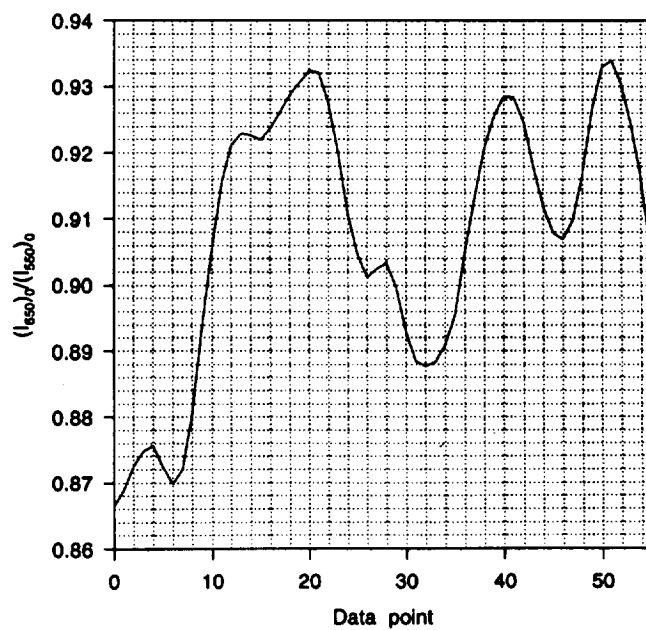


Figure 3.17. Two-color paint red and green flow-off ratio

The distribution of a multi-ratio $[I_{650}/I_{550}]_0/[I_{650}/I_{550}]$ is shown in Figure 3.18. If the temperature coefficients of the two luminophores are the same, the temperature effects would be removed, although this is not the case. The intensity distribution is very similar to the distributions in Figures 3.7 and 3.12. More noise is associated with this method because of the multiple divisions needed to create the intensity plot. This can be eliminated by averaging more scans and measuring the two wavelengths at the same time using two photomultiplier tubes.

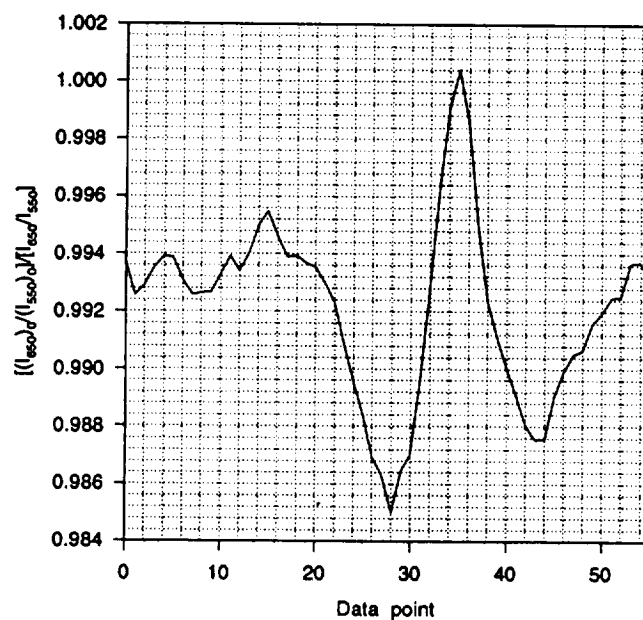


Figure 3.18. Two-color paint multi ratio

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